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MarsNet: A Mars Orbiting Communications & Navigation Satellite Constellation[1]

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Abstract— Mars has become the focus of an unprecedented series of missions spanning many years, involving numerous nations and evolving from robotic to human exploration. Elements will be dispersed widely in longitude and latitude over the surface of Mars. Some surface elements like rovers, balloons and airplanes will be mobile. Other elements like sample canisters will orbit Mars. Finally manned sites will require broadband, 24hr connectivity to earth. The challenge has been to develop an architecture and technology roadmap that will anticipate the needs of this evolving mission set. NASA's Jet Propulsion Laboratory has begun development of this architecture and its associated technologies. The architectural system design is presented along with the resulting telecommunications and navigation performance it provides to Mars in-situ elements.

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1. INTRODUCTION

Western civilization's expansion into and throughout the Americas was preceded by exploratory missions like those of Columbus and the Lewis and Clark party. These exploratory missions were then followed by early outposts and eventually waves of colonization. The path to Mars follows an analogous sequence with the twist that current technology allows us to preface human sorties with robotic exploratory missions and robotic outposts. To date, most of the Mars missions fall into the exploratory class where each mission is self contained and carries its own telecommunications and navigation hardware to connect it with Earth. Future missions will involve multiple spacecraft and landed elements that will share Comm and Nav support infrastructure that remains in-place at Mars over many years. [1] This long-term vision includes a network of Mars orbiting spacecraft, MarsNet, that will provide Mars global communications and navigation services within the Mars arena, element-to-element, and act as a relay point for high bandwidth communications to/from Earth.

There are several key advantages to this approach.

1) The mass and volume of telecom hardware needed to communicate over the long haul link to earth is off-loaded to the MarsNet spacecraft. This allows for more science payload on standard landers and rovers and enables a new class of very low mass, less than 5kg, microlander and microrover missions.

2) Sharing Comm and Nav resources across a number of missions, NASA can afford to deploy the MarsNet constellation that provides global coverage of Mars and enables in-situ positioning service.

3) As Mars mission operations gain more autonomy from Earth, they require low latency Comm and Nav functions. The MarsNet system provides short hop communications between elements within the local Mars environment.

4) A portion of the science mission risk is removed by having Comm and Nav resources in place at Mars and working. As an example, the Mars Climate Orbiter spacecraft was expected to provide backup relay telecom for the Mars Polar Lander. Its recent loss has left the Polar Lander mission scrambling for other backup telecom options.

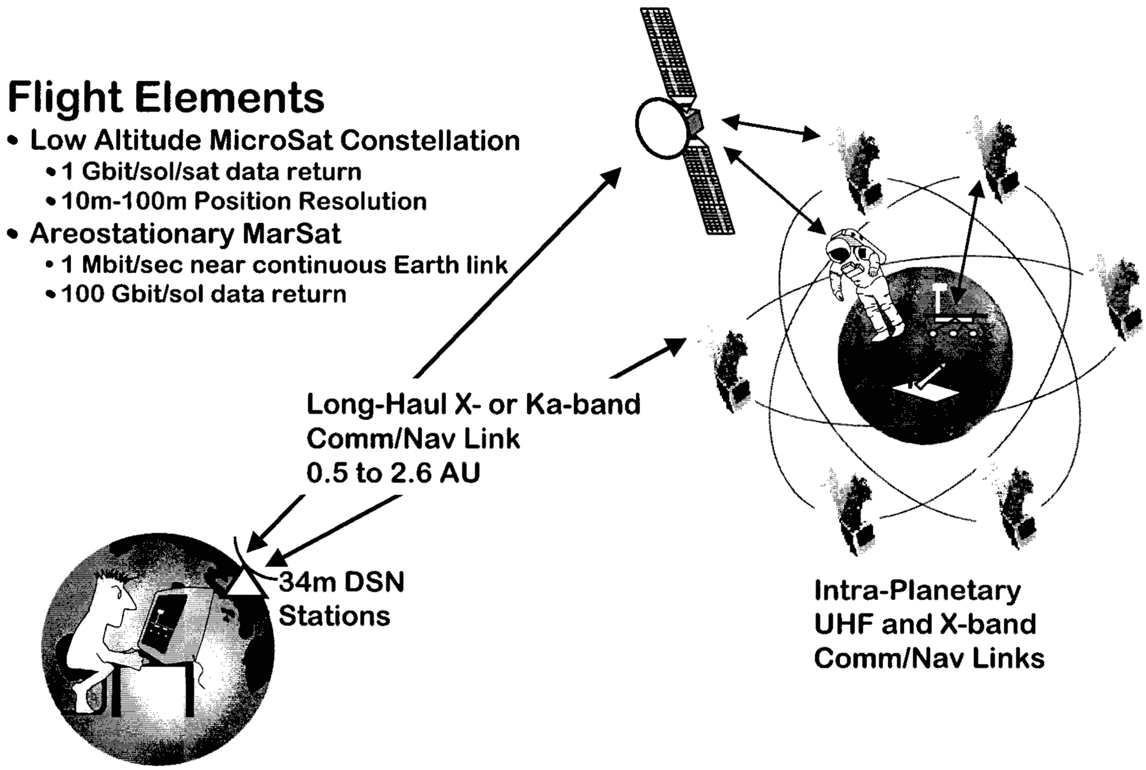

Figure 1 - Mars Network Overview

MarsNet is envisioned as an extension to the existing earth-based Deep Space Network, (DSN), managed by the Telecommunications and Mission Operations Directorate, (TMOD), at the NASA Jet Propulsion Laboratory, (JPL). In FY99, funded by the NASA Space Operations Management Office (SOMO), TMOD conducted a MarsNet Phase A study that is expected to proceed into program approval and implementation beginning in FY00.

This paper presents a high-level overview of the envisioned MarsNet architecture, evolution and the service performance it provides.

2. Architectural Overview

The Mars communications and navigation infrastructure, depicted in Figure 1, comprises three main elements. The first of these is a set of Mars-orbiting, low-altitude micro-satellites (MicroSats). Extensive analyses and numerous studies over the last few years have consistently demonstrated the benefits of low-altitude Mars relay satellites for support of landed elements. [2,3,4,5,6] The currently envisioned MicroSats are to be launched as piggyback payloads on the Ariane 5 launch vehicle and take a "banana" shape to fit on the Ariane auxiliary payload ring. One MarsNet MicroSat concept is shown in figure 2 with the high gain X-band earth link dish deployed.

After spending time in a near-Earth phasing orbit, MicroSats will depart for Mars, arrive after a 6 to 11 month trans-Mars flight time and insert into an elliptical capture orbit. After a 3-4 month, aerobraking phase a periapsis raise maneuver will place the MicroSat into its final low altitude circular orbit.

Figure 2 - MarsNet MicroSat Concept

Wet mass is on the order of 220 kg at launch, of which 140 kg is propellant necessary to accomplish all ΔVs to arrive at the operational Mars orbit. Roughly 1 kg of propellant is budgeted for orbit maintenance over a 5 year lifetime. The Earth link payload mass is 5 to 7 kg comprising an X or Ka-band transponder, amplifier, switches, filters, diplexer, antennas and optionally a USO. Operating at 10 to 150 kbps per second, the Earth link can return Gigabits of data per day to a standard 34m DSN earth station.[7] The UHF payload used for all in-situ communications and navigation is limited to 6 kg.[8] In this modest allocation is packaged all of the in-situ telecom and navigation elements. Upcoming analysis in this paper will describe its performance.

A first MicroSat is expected to depart for Mars in the 2003 opportunity and to eventually take up residence in an 800 km, near equatorial orbit. At each succeeding Earth-to-Mars opportunity (~ 26 months), two more such spacecraft will be dispatched to Mars, targeted for near-equatorial and high inclination orbits as needed. Equatorial orbiters provide excellent connectivity to low-latitude landed-elements, which are expected to include most sample return operations. Highly inclined orbiters round out the constellation by providing global coverage for the benefit of high-latitude surface elements. Six satellites are nominally planned for the steady-state constellation. More would be desirable, especially for real-time positioning, but budget constraints will likely preclude this.

The second element consists of a small number of Mars-orbiting areostationary satellites (MARSats). Because of the ΔV requirements to attain this high-altitude orbit, these must be heavier, more expensive, prime launch vehicle payloads and hence limited in number. Nevertheless, they will provide increased Earth link performance, 100 Gigabit per day, increased surface link capacities and nearly continuous coverage over most of the Martian hemisphere under their stationary longitudes. The first of these assets will launch at the 2007 Earth-to-Mars opportunity at the earliest. They will eventually provide the high-capacity link that will be required as the near-term robotics program transitions to robotic outposts and then to the set of missions culminating in humans on Mars. The necessary equatorial orbit and lack of orbital dynamics will minimize the utility of the areostationary satellites for global positioning. (Electric Propulsion for the MARSats)

A third element of the overall architecture is the set of large deep space tracking antennas located on Earth. These will primarily comprise the antennas of NASA's Deep Space Network, located in the California desert, Spain and Australia.

3. Mars Mission Requirements

Selecting a baseline constellation design for the Mars Network begins with consideration of the user's requirements for both communications and position location service. These requirements are prime drivers for developing the Network's needed functional capabilities. Several planned near-term Mars missions are designed to utilize in-situ UHF relay support. However, these missions were designed without assuming the potential benefit of Mars Network MicroSats. For the 2003 opportunity, the following missions are in planning or development:

- Micromission Aircraft — Short 15–30 minute flight mission using remote sensing instruments on 17 Dec 2003 (100^{th} anniversary of Wright Brother's flight) with simultaneous UHF relay transmission via the Micromission Carrier spacecraft, which is targeted to over-fly the aircraft during closest approach of its Mars flyby. Maximum total data return desired (> 1 Gb). Backup relay support by the Mars Surveyor (MS) '01 Orbiter or an '03 MarsNet MicroSat.

- Mars Sample Return (MSR) Lander — Three month mission in equatorial zone culminating in launch of Mars Ascent Vehicle containing Mars rock, soil and air samples. 2-way communications between the Rover and Lander via S-band. A 2-way Lander-to-Earth X-band link is used for commands and return of 70 Mb/sol. UHF link to orbiter may be used to supplement and back up the direct-to-Earth link. Desired Doppler surface location determination < 1 km.

- MSR Rover — Delivered by MSR Lander for three-month sample gathering primary mission with possible 3-month extended mission. Two-way communications via S-band link with MSR Lander or via UHF link with an orbiter. Desired Doppler surface location determination < 1 km.

- MSR Canister — Rides on the Mars Ascent Vehicle and injects into 600 km altitude, 45 degree inclined parking orbit for later retrieval by '05 MSR Orbiter/Earth Return Vehicle. Has low power UHF transponder, that provides a continuous Doppler signal while in sunlight. This signal will be received (probably open loop) by the MS'01 Orbiter, Mars Express or an '03 MarsNet MicroSat for orbit determination. (Mars Express is a joint Project of the European Space Agency (ESA) and Agenzia Spaziale Italiana (ASI), comprising a remote sensing orbiter and lander to be launched in the 2003 opportunity.)

- Beagle-2 — Search for life landed element of the Mars Express Project, delivered to Mars for a 180-day mission at a site within the 0 to 35 degree latitude range. Average relay data return via Mars Express is 15 Mb/sol with contacts every 4 or 5 days. Greater number of contacts and data return are desired.

For the 2005 opportunity, the following missions are in planning or development:

- MSR Lander, Rover, and Canister — Repeat of '03 missions at another near equatorial site.

- <u>Netlanders</u> — Four stations, performing geodetic, seismic, climate and other network investigations, delivered by the MSR'05 Orbiter for one Mars year, (687 days), of surface operation at dispersed longitude sites within ± 35 degree latitude. Average relay data return via Mars Express is 10 Mb/sol/lander with contacts every 4 or 5 days. Augmented support is desired.

- <u>Micromission probe(s)</u> — are under consideration for the 2005 opportunity.

The above near-term missions illustrate the very active interest in Mars exploration. The mission requirements and designs for future opportunities are, of course, less well defined. For the 2007 and following launch opportunities, NASA is considering the options of additional sample return missions and the initiation of robotic outposts. Several small-scale probe missions, such as those that can be delivered by Micromission carriers, have been proposed. Challenging sensor network missions are also being considered. The science and public interest in these missions is expected to continue, increasing the requirements for higher data volume and connectivity as well as global positioning capability.

Although the MS'01 Orbiter and Mars Express are expected to provide relay support for missions launched in '03 and '05, no known additional science orbiters are planned which would provide future relay capability. Therefore, implementation of an evolving MarsNet should provide the needed future relay capability.

For substantially higher data volume and more continuous connectivity, as would be expected to be required for robotic and human outpost missions, the Network areostationary MARSats would be deployed. The remainder or this paper will focus on the design and performance of the lower cost near term constellation comprised only of low altitude MicroSats

4. Design Goals and Performance Metrics

Performance Goals

With the previously described users in mind, the performance goals listed below have been identified as having a primary influence on the constellation design of the Mars Network.

1) Provide global coverage. Dispersed mission types, such as seismic or meteorological networks, require global communication support. The practical result is to deploy spacecraft in inclined orbits providing coverage across all latitudes.
2) Provide high capacity, low latency communication support of the equatorial regions. The bulk of the currently identified Martian surface elements will be located at low latitudes. Additionally, the first human missions are planning near equatorial landing sites. The practical result is to deploy a portion of the network in near equatorial orbits.
3) Maximize coverage and performance across all latitudes and longitudes.
4) Minimize coverage and performance variations across all latitudes and longitudes, with the exception of designing in enhanced support to the near-equatorial region.
5) Provide maximum utility during buildup of the constellation.
6) Provide redundant coverage of all regions. The loss of any single MicroSat should not compromise the goals of global coverage and enhanced service to near equatorial latitudes.
7) Minimize coverage variability due to long-term orbit perturbations. In particular, minimize the impact of orbital precession on the coverage geometry. Minimize orbital maintenance as measured in operations time/cost and expended Delta V.

Since the MarsNet constellation serves the user's communications and navigation needs simultaneously, design trades between these functions must be considered in orbit selection. Where there are trade-offs, there need to be metrics by which various design alternatives can be compared. Two generic coverage metrics were used and two specific Comm and Nav performance metrics were defined. For each constellation considered, these metrics were evaluated across all latitudes and longitudes and then averaged across longitudes to simplify graphical presentation.

Coverage Metrics

<u>Passes/Sol</u> – Indicative of the temporal coverage and number of opportunities per sol to contact a surface element through the MarsNet constellation.

<u>Maximum Gap Time Between Contacts</u> – Combined with metric Passes/Sol, gap time shows how evenly the contacts are dispersed. Shorter maximum gap times indicate higher capacity and more even coverage of sites.

The coverage metrics are very important for mission planners. In particular mission operators prefer flexibility and repeatability in planning their command and data return events. More passes/Sol indicates more event opportunities. Shorter max gap times indicate a more regular spacing or timing of pass opportunities. Hence the constellation should strive to maximize Pass/sol and shorten the maximum gap time.

Comm/Nav Metrics

<u>Mbit/Sol/Watt</u> – The "tuning" of MicroSat orbit elements not only changes the data rate capability but also the

number and duration of passes to ground sites. Thus data capacity per Sol, rather than instantaneous data rate is the better metric. In addition, the demand on Mars in-situ data bandwidth is asymmetric. It is the data return link that requires high capacity. We have defined a reference Mars Surface to MicroSat Comm link under the following assumptions:

- Xmit Antenna - 0dBi omni
- Xmit Power – 1 watt
- 400 MHz operating frequency
- BPSK signaling, 70 degree modulation index
- Rcv Antenna – 0 dBi omni
- Rcv System Noise Temp – 500 Kelvin
- Xmit and Rcv Polarization and Feed Losses – 3 dB
- Receiver Losses – 2.8 dB
- Threshold Eb/No = 3.2 dB, (K=7, R=1/2 with (255,223) R-S Code, Corresponding to a BER of 1 x 10e-6 for non-interleaved codes.
- Minimum elevation angle of 15°

Mean Response Time (MRT) – Average time to collect sufficient measurement observations to compute a user's position to a prescribed accuracy. Minimizing the time to collect accurate position observations is key to the success of rover operations. The following assumptions have been used in computing Nav metric.

- User position accuracy goal is 10 m (1σ RSS). The 3-D position error is calculated as the RSS value of the errors in X,Y and Z coordinates.
- 2-Way Doppler measurement uncertainty of .5 mm/sec at 60 sec (1σ)
- 1-Way or 2-Way Range measurement uncertainty of 1m (1σ).
- User clock fractional frequency stability of 10e-11 for 60 sec. When estimating position using 1-Way range it is assumed that the clock errors are estimated simultaneously. The satellite clock is considered to be perfect for analysis purposes (a current specification for this clock is 10e-14 for 60 sec).
- Orbit errors are considered at a level of 2m radial (1σ), 7m along track (1σ) and 7m cross track (1σ). (These error levels are consistent with the new Martian gravity field MGS75B developed from data collected by the Mars Global Surveyor satellite).
- Atmospheric error and other error sources are neglected

An additional communication metric that has been considered while analyzing the various constellation geometries is the Data Return/Joule – a data quantity metric for energy limited missions. Energy limited missions are those that arrive with a fixed energy supply (e.g. the Deep Space-2 Mars surface penetrator), and have no means of recharging this supply. When the battery is depleted, the mission is over. Since radiated RF energy is dispersed according to the square of the slant range; the shorter the slant range, the less total energy that is expended per bit. This energy metric is always improved by using lower altitude spacecraft and higher elevation angles for communication.

Before discussing specific constellation results, several general comments can be made regarding telecom and positioning performance that apply to all the constellations studied.

Range squared power losses dominated the telecom metric. While lower altitude orbits generally produced fewer and shorter passes for any particular surface site, the shorter ranges cause the metric Mbit/Sol/Watt to increase continually while orbit altitude is lowered down to 400km or less. In addition, no combination of elliptical orbits was found that could provide better telecom performance than a constellation comprised of spacecraft only in circular orbits.

Since our sparse constellation results in few instances where multiple satellites are in view from a single surface site, position solutions are built up from sequential observations made by individual satellites. Short gap times and varied observational geometries improve the navigation metric. This favors spacecraft at altitudes above 1000km which provide more frequent and varied observation geometries of a single surface site from different spacecraft.

5 – Constellation Comparisons

Several constellation scenarios have been analyzed and compared, the candidate constellations' parameters are given in table 1 below.

The coverage metrics, Passes/Sol and Maximum Gap Time, for these constellations are displayed in figures 3 and 4 respectively. Figure 5 shows the Data Volume that can be returned through each constellation from a single surface element. Note that the data return numbers are listed as Mbits/Sol/Watt. If a surface element has 10 watts Effective Isotropic Radiated Power, EIRP, then the data return numbers scale up by a factor of 10. Figures 6 and 7 display the positioning Mean Response Time (MRT) for the candidate constellations using 2-Way Doppler data and 2-Way range data, respectively.

Table 1: **Primary candidate constellations considered for the Mars Network**

SatID	*Multi-Inclined* (h,i,Ω,M) (km,deg,deg,deg)	*4inc65* (h,i,Ω,M) (km,deg,deg,deg)	*4retro111* (h,i,Ω,M) (km,deg,deg,deg)	*4inc80* (h,i,Ω,M) (km,deg,deg,deg)
1	(800,10, 0,0)	(1100,10, 0, 0)	(800,172, 0, 0)	(1100,10, 0,0)
2	(800,35, 60,0)	(1100,10,180, 0)	(800,172,180, 0)	(1100,10,180,0)
3	(400,55,120,0)	(1100,65, 0, 0)	(800,111, 0, 0)	(400,80, 60,0)
4	(400,65,180,0)	(1100,65, 90, 90)	(800,111, 90, 90)	(400,80,120,0)
5	(400,75,240,0)	(1100,65,180,180)	(800,111,180,180)	(400,80,240,0)
6	(400,85,300,0)	(1100,65,270,270)	(800,111,270,270)	(400,80,300,0)

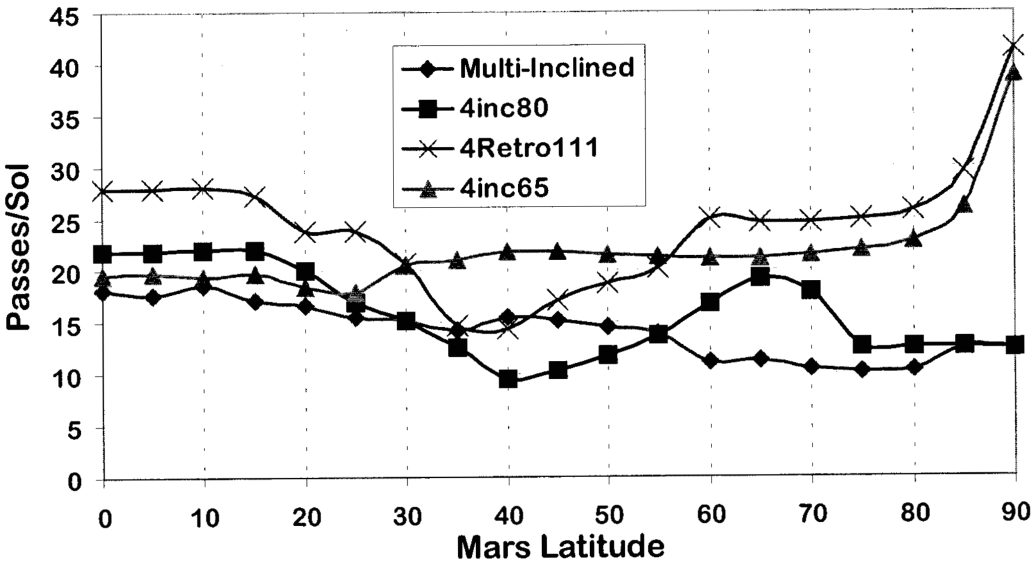

Figure 3 - MarsNet MicroSat Concept

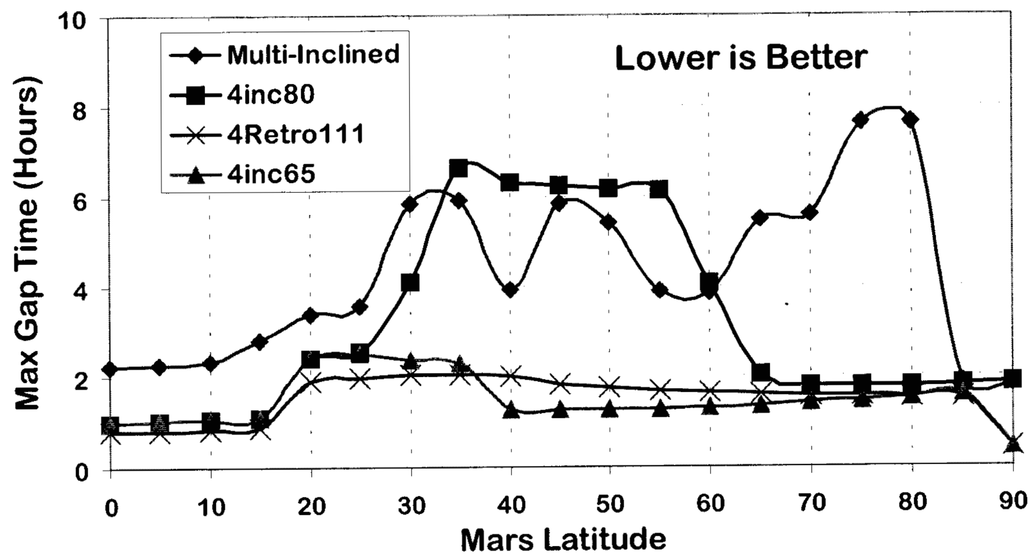

Figure 4 - Max Gap Times Associated with Candidate Constellations

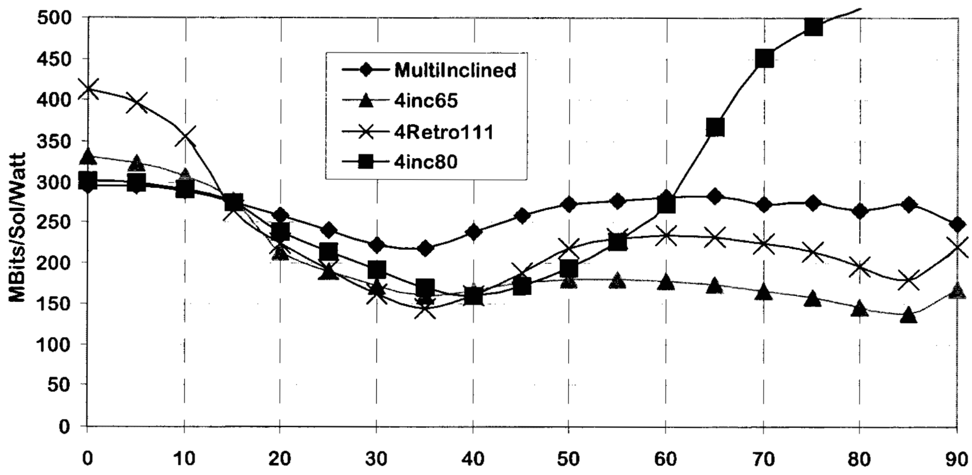

Figure 5 – Mbits/Sol/Wat Provided by Candidate

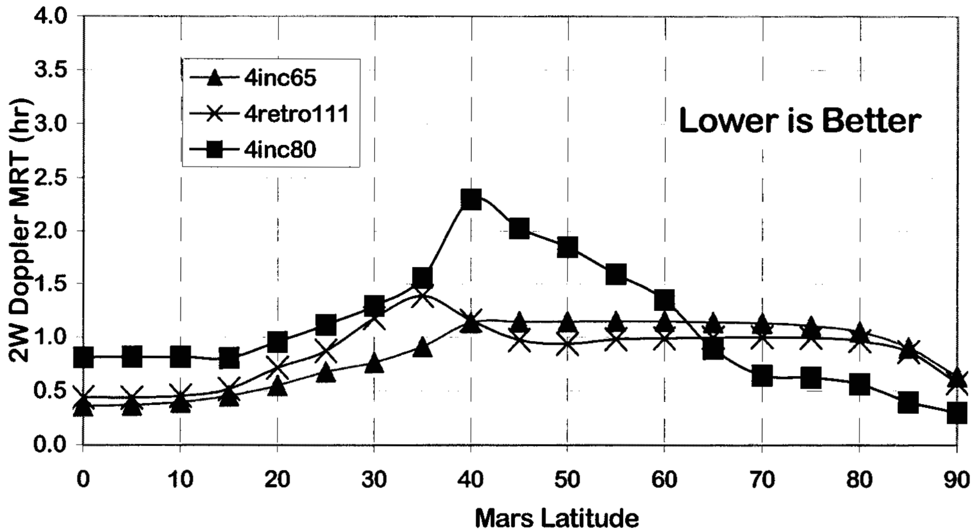

Figure 6 – Mean Response Time to Achieve < 10m Uncertainty in Position Using 2-Way Doppler

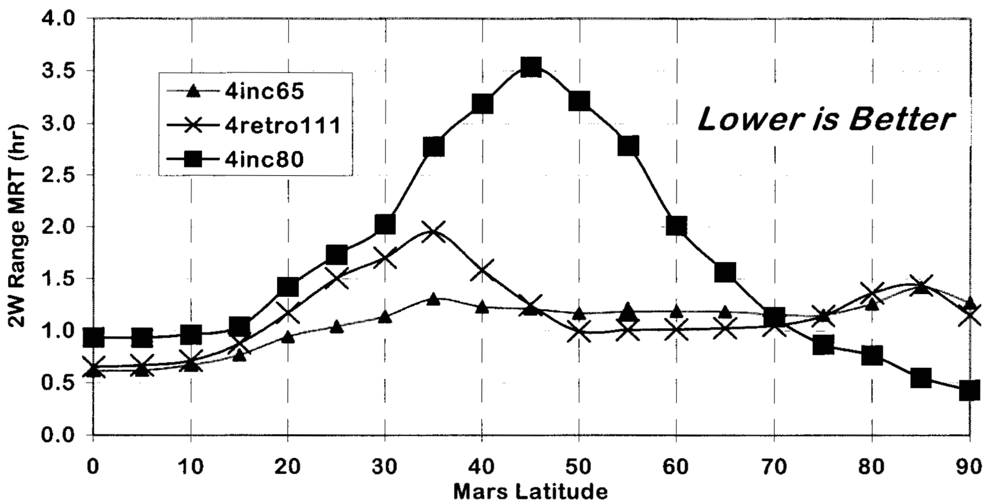

Figure 7 – Mean Response Time to Achieve < 10m Uncertainty in Position Using 2-Way Range

Multi-Inclined Constellation

A useful rule of thumb for optimizing low altitude satellite coverage to a specific ground site is as follows: For best support of surface elements at latitude X, put a spacecraft in an orbit that is inclined X degrees with respect to the equator. A simple extension of this heuristic suggests that a constellation that is comprised of a series of satellites distributed across many inclinations would provide good distributed coverage of the planet. Following this approach, a 'Multi-Inclined' constellation was defined, with orbital elements fairly evenly distributed across inclinations from 0 to 90 degrees and ascending nodes distributed from 0 to 360 degrees. As seen in figure 5, this type of constellation indeed provided reasonable coverage and very high data return over all latitudes. Unfortunately the specific orbit phasings that achieved this optimum communications performance are destroyed in a few weeks by differential perturbations induced by the Martian gravity field. Without fuel expensive orbit maintenance, every 3 months the constellation is pulled into an arrangement where the ascending nodes of many of the orbits are no longer dispersed, but are bunched together. These poor geometry conditions can last for several weeks with maximum gap times at some locations exceeding 6 hours. Worst case degeneracies occur every 2 years which result in maximum gap times at some locations in excess of 10 hours.[7] This is unacceptable and thus the specific Multi-Inclined constellation and its variants were dropped from further consideration.

Common among the constellations that maintain consistent high performance is a pair of near equatorial orbiters to provide regular communications opportunities for low latitude surface elements. This equatorial sub-constellation is combined with 4 high inclination orbiters that share the same inclination and altitude. With inclined orbiters precessing together, the constellation is able to provide consistent long-term coverage. Finally, the selection of orbital altitude was influenced by tradeoffs between strength of the radio link and gap time between contacts. Low altitude constellations are characterized by strong links, but longer gap times. Higher altitude constellations have a weaker link, albeit with shorter gap times between contacts. Reduced gap times aid in quick position location of surface elements.

4inc80 Constellation

The '4inc80' constellation provides good total data return per sol across all latitudes; however communications performance favors the poles rather than the equatorial region. This conflicts with Performance Goal 2 that requires focused support near the equator. Furthermore the low altitude of the upper sub-constellation requires the use of a high inclination to provide coverage up to the pole. The result is poor performance at the mid-latitudes as compared to the other constellations in this study. The low altitude associated with the 80° inclined spacecraft yields a swath width that covers less surface area than the higher altitude constellations, and produces longer gap times in the mid-latitude locations. The impact of this effect is most notable with the positioning performance.

Figures 6 and 7 show that, worst case, the Mean Response Time, MRT, for both range and Doppler measurement type is nearly twice as long as with the other constellations. The only region where 4inc80 yields superior positioning performance is above 70° latitude.

4Retro111 Constellation

To reduce position fix Mean Response Time in the mid-latitude regions the high inclination sub-constellation must be adjusted. In particular we must lower the inclination angle and raise the orbit altitude to maintain full 0 – 90 degree latitude coverage while lowering gap times and providing improved coverage to the mid-latitude region. At an altitude of 800km, the '4retro111' constellation is a reasonable choice. Compared to the 4inc80 constellation, the result is a factor of 1.5 to 2 reduction in position fix mean response time for latitudes below 65 degrees. The poor MRT performance hump in the mid-latitude region is flattened considerably. Overall MRT remains below 1.5 hrs for Doppler data and 2 hrs with range data. Even though the altitude has risen, acceptable data volume numbers are maintained, and it has the best communications performance near the equator of all constellations considered.

Initially, this constellation configuration was analyzed in a prograde orientation, called 4inc69. However, in this orientation, trajectory analysis of the aerobraking phase for the initial satellite revealed eclipse times that are significantly larger than a maximum allowed value of 2 hours. Changing the inclinations from prograde to retrograde reduced the maximum eclipse times below this threshold. Navigation and communication performance between the two constellations is practically identical, although the pass time statistics differ. The retrograde orientation has more passes of shorter duration than the prograde case and the maximum gap time is reduced. Because of its superior pass statistics and shorter duration eclipses, the retrograde orientation of the 4inc69 was selected, specifically 4retro111.

4inc65 Constellation

The '4inc65' constellation focuses on increasing the orbit altitude another notch to 1100km in an effort to further reduce gap times. The navigation performance improvements of this constellation are marginal, and come at the cost of a reduced data volume in the mid to northern latitudes. Furthermore, obtaining a higher altitude requires a larger periapsis raise maneuver after aerobraking is complete. The spacecraft is very weight constrained, and the additional delta-V that this maneuver requires adds to an already tight mass budget. Because of these factors selection of this constellation is not warranted. The present conclusion is to baseline the 4retro111 constellation. Its performance characteristics meet the combined communication and navigation goals better than any of the other constellations examined. The next section on constellation evolution addresses 4retro111's utility during buildup, Performance Goal 5, and redundant coverage in the event of a loss, Performance Goal 6.

An examination of the range results suggests that range is not as good a data type as Doppler, however this conclusion cannot, in general, be made. Both the range and Doppler performance seen in figures 6 and 7 are impacted by the selected noise values and the simplifications made to model the orbit error. It is anticipated that the actual range noise specifications for the Mars Network will be 10 cm (1σ), an order of magnitude improvement. This combined with improvements to the orbit error modeling may produce a more favorable comparison between the range and the Doppler results.

Mars Net Evolution

It is necessary to understand how the telecommunications and navigation performance of the 4retro111 constellation evolves as spacecraft are deployed every 2 years. Table 2 lists the deployment strategy starting with the prototype satellite in its final orbit at Mars in 2004, ending with the constellation in its final configuration in 2011. Figure 8 depicts the max gap, Comm and Nav performance metrics for the constellation as it is deployed. Note how the prototype near equatorial spacecraft only provides coverage out to ±30° latitude and gap times start to deteriorate rapidly outside 10° latitude. As discussed earlier, elements within 15.6° of the equator receive a pass on every orbit while elements above 15.6° begin to miss passes, and, thus, gap times deteriorate. Nevertheless, this single orbiter provides a significant capability.

For users located between ±15° latitude, communication volume is greater than 87 Mbits/Sol/Watt, and positioning to 10 m uncertainty takes under 3 hrs.

On the second launch opportunity two additional Comm/Nav orbiters are planned with their final orbits attained in 2006. The constellation consists of three elements, two near equatorial at 172° and one inclined at 111°. The inclined spacecraft ensures that all locations on Mars get service. The max gap statistic shows a worst case revisit time of 13-14 hours for the higher latitudes. The implication is that users in these regions are now guaranteed a minimum of roughly two passes per sol. The average is 5 passes per sol. The additional equatorial orbiter is phased 180° from the first equatorial orbiter in ascending node. This evenly distributes coverage over the north/south near-equatorial latitudes and provides revisit times of less than 1 hour out to ±10° from the equator, and less than 2 hours out to ±20° from the equator. This installment provides a significant *global* communication and navigation capability. *All* potential users receive a *minimum* of 40 Mbits/Sol/Watt communications volume, and 10 m position accuracy within a MRT of less than 6 hrs.

The third deployment opportunity in 2008 sees one more equatorial and one more inclined orbiter deployed. The prototype equatorial orbiter is assumed to be dead by this time, thus the constellation now consists of two equatorial and two inclined orbiters. The second inclined orbiter dramatically reduces max gap times above 50 degrees latitude. Naturally, the communication and navigation performance is enhanced primarily in the mid and upper

Table 2: 4retro111 Constellation Buildup Plan

Injection into Trans-Mars Trajectory	*May '03*	*September '05*	*September '07*	*October '09*
Mars Orbit Insertion	*December '03*	*March '06*	*August '08*	*September '10*
Finish Aerobraking	*April '04*	*July '06*	*December '08*	*January '11*
Microsat 0[2]	172°	------		
Microsat 1		172°	------	------
Microsat 2		111°	------	------
Microsat 3			172°	------
Microsat 4			111°	------
Microsat 5				111°
Microsat 6				111°

[2] prototype, not part of the final constellation

latitude regions.

Finally, on the fourth deployment opportunity, adding two more inclined orbiters completes the constellation. At this point the revisit time to any location on Mars is less than 2 hours on average, with a worst case less than 4 hrs, and each location is visited on average 15 or more times per sol. In the final configuration, all users receive a *minimum* support of 140 Mbits/Sol/Watt communications volume, and 10 m position accuracr within a MRT of 1.5 hrs.

The performance histories shown in figure 8 illustrate the ability of the constellation to provide capable, although somewhat degraded performance, with the loss of a single spacecraft (Goal 6). For instance, the difference between the 2008 and 2006 configurations is one inclined spacecraft. Hence, the differences in performance between these two configurations are equivalent to the impact of a loss of an inclined spacecraft. Clearly, the 2006 constellation is able to meet the Network's fundamental mission, although its performance is somewhat degraded from that of the 2008 configuration. The buildup history also supports the claim that each successive installment of the 4retro111 constellation provides improving utility (Goal 5). A current area of

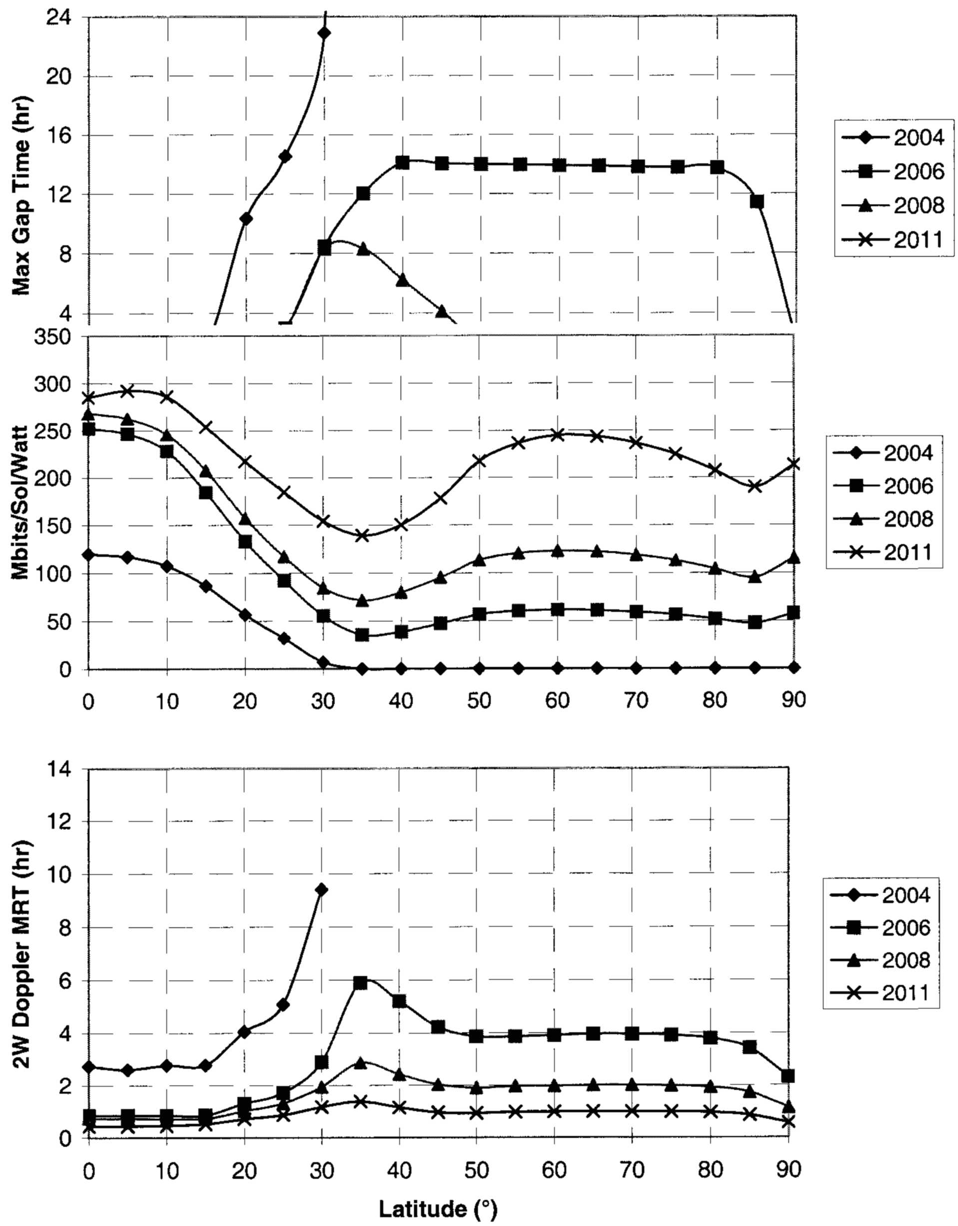

Figure 8 - 4retro111 constellation build up performance for the maximum gap time (top), data volume (middle), and mean response time using 2W Doppler data to achieve a position uncertainty of < 10m (bottom).

investigation is aimed at optimizing the constellation parameters and the buildup plan in a systematic way. The continuing effort utilizes a genetic algorithm on a design space that includes altitude, inclination, ascending node phasings, and mean anomaly phasings.

6 – Conclusions

The expansion of science activities at and around Mars over the next 10 years will require increased communications and navigation support. We have shown that a sparse constellation of only 6 satellites of low altitude spacecraft at Mars will service the communication and navigation needs of users at Mars while, simultaneously, decreasing the support needed from Earth

Common among the constellations that had both high performance and stable coverage characteristics over time was a pair of near equatorial orbiters to provide regular communications opportunities for low latitude surface elements. This equatorial sub-constellation is combined with 4 high inclination orbiters that share the same inclination and altitude. With inclined orbiters precessing together, these constellations are able to provide consistent long-term coverage.

The selection of orbital altitude was influenced by tradeoffs between strength of the radio link and gap time between contacts. Low altitude constellations, 400km altitude, are characterized by a high volume of data return, but longer gap times. Higher altitude constellations, 1000km to 2000km, return less data per contact or per sol, albeit with shorter gap times between contacts. Reduced gap times aid in quick position location of surface elements. The chosen constellation, 4retro111, compromised these competing altitude drivers and placed all spacecraft at an altitude of 800km.

The 4retro111 constellation design is robust, in that, a loss of a single satellite yields no catastrophic degradation in global support. Indeed even of partial constellation of only 4 spacecraft achieves all of the performance goals, albeit with degraded performance. In its final 6 satellite configuration the 4retro111 constellation provides to any Mars surface location a *minimum* support of 140 Mbits/Sol/Watt communications volume, and 10 m position accuracy within a Mean Response Time of 1.5 hrs. It will enhance the current planned missions, and it will enable the development of future, envisioned missions to Mars.

Current efforts are focused on iterating the present design using a systematic search of the reasonable design space for an optimal constellation. A trade-space search using Genetic Algorithm techniques and a maximum gap time metric is under way now. Other areas of continuing work include improvements in the orbit error modeling of the navigation performance tools, long term perturbation studies, orbit maintenance Delta V requirements and trade-offs of spacecraft hardware and operations options to increase data volume per pass and per sol.

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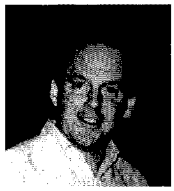
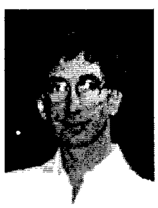
and a recipient of the NASA Exceptional Service Medal.



David J. Bell received his B.S. degree in Electrical Engineering in 1980 from Cornell University and his M.S. in Electrical Engineering in 1981 from Stanford University. His work at the Jet Propulsion Laboratory for the Advanced Communications Concepts Group has involved front-end research and development in support of new commercial satellite services and spacecraft communications in support of NASA's deep space missions.

In the 80's, Mr. Bell focused on Satellite Mobile Communications, working on the development of vehicular antenna systems, Satellite-Mobile RF channel characterization and modeling and development of demonstration hardware. In the early 90's Mr. Bell worked on Satellite Broadcast Digital Radio. His work involved the development of system designs, modulation/coding, equalizer design, Comm-system computer simulations and development and test of satellite service demonstration hardware. In 1996, Mr. Bell was co-founder and President of Universal SpaceNet, the first company to offer commercial telemetry, tracking and control services. Based in Newport Beach, the company is offering these services today.



Robert Cesarone is currently involved in program management, strategy development and long range planning at the Jet Propulsion Laboratory. His activities specifically involve telecommunications and mission operations, including the development of architectural options for the Deep Space Network, NASA's network for tracking interplanetary spacecraft. He has held his present position since September 1991 and has been employed at JPL since 1977. Prior to his current assignment he has held a number of positions within the Voyager Navigation Team, in particular that of lead trajectory and maneuver engineer for the Voyager 2 flybys of Uranus and Neptune.

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